Environmental Management (2008) 41:573–583
DOI 10.1007/s00267-007-9063-5

ENVIRONMENTAL ASSESSMENT

The Effects of a Dredge Excavation Pit on Benthic Macrofauna in Offshore Louisiana

Terence A. Palmer · Paul A. Montagna · Robert B. Nairn

Published online: 5 February 2008

Abstract Over two years after the original creation of a sand excavation pit 8 km off the Louisiana coast, benthic macrofauna communities and sedimentary characteristics are still effected. Macrofaunal communities inside the pit had lower abundance, biomass, and diversity than communities outside the pit. This difference, however, was only significant with some of the stations outside the pit. Results from multi-dimensional scaling and cluster analysis showed that macrofaunal communities were less than 32% similar inside the pit to communities outside the pit. The polychaete *Mediomastus ambiseta* was the most abundant species outside the excavation pit, but the species was only counted once inside the pit. The most dominant species, which made up over 90% of organisms inside the pit, was the pioneer polychaete *Paraprionospio pinnata*. Only three species were found at each station inside the pit as opposed to 9–27 species at stations outside the pit. All species inside the pit were also found outside the pit; thus, change was due to a loss of species rather than replacement by different species. Sediment inside the pit contained more silt and clay; however, no difference in water quality was detected compared with outside the pit. Hurricanes Katrina and Rita passed near the dredge pit in 2005 and could have effected sediment transport in the region. Because the macrofaunal community inside the pit has not recovered within 38 months, it is likely that it will require more time before it resembles the surrounding conditions.

Keywords Macrofauna · Benthic · Sand excavation · Dredge · Louisiana · Gulf of Mexico

Introduction

Sand for beach nourishment is often obtained by offshore dredging because of the large volumes of sand required and also because offshore dredging does not have the obvious impacts of nearshore and onshore sand mining (Hilton 1994; Byrnes and others 2004; Work and others 2004; Finkl and Khalil 2005). Offshore dredging, however, still leaves excavation pits that are often physically different from the original and surrounding environment. These physical changes can in turn impact organisms inhabiting the excavated area, especially the benthos. The potential impacts on benthic organisms in an excavated pit can occur by three mechanisms: defaunation of sediment by the dredging process; physical changes to the water column caused by stratification within the pit; and change in sediment size and dynamics in and around the pit (Nairn and others 2004).

Dredging directly causes defaunation of sediment. Colonizers of defaunated sediment are typically dominated by fast growing, opportunistic *r*-selected macrofauna species (Pearson and Rosenberg 1978; Rhoads and others 1978; Thistle 1981; Lu and Wu 2000). Benthic colonizers are often small polychaetes, especially from the Spionidae and Capitellidae families (Grassle and Grassle 1974; Pearson and Rosenberg 1978; Montagna and Kalke 1992; Palmer and others 2002). Unless there is subsequent frequent disturbance, succession occurs where colonizers are replaced

T. A. Palmer (✉) · P. A. Montagna
Harte Research Institute for Gulf of Mexico Studies,
Texas A & M University-Corpus Christi, 6300 Ocean Drive,
Corpus Christi, Texas 78412-5869, USA
e-mail: terry.palmer@tamucc.edu

R. B. Nairn
W.F. Baird & Associates, 627 Lyons Lane,
L6J 527 Oakville, Ontario, Canada

or joined by a more diverse range of larger *k*-selected species (Pearson and Rosenberg 1978; Ritter and others 2005).

Changes in the water column directly above an excavated dredge pit could inhibit the macrofaunal community from developing into a community that would represent its pre-dredging state. The two mostly likely water column changes are a short-term increase in total suspended solids (TSS) immediately after dredging and the formation of hypoxic (low oxygen) conditions occurring partially as a result of water column stratification in the pit. Hypoxic conditions (low oxygen) are generally defined in the northern Gulf of Mexico as water with less than 2 mg l^{-1} (Pokryfki and Randall 1987; Rabalais and others 2002). The threshold was defined as 2 mg l^{-1} because bottom-dragging trawls do not usually capture shrimp or demersal fish below this concentration (Renaud 1986). At low oxygen levels, pericaridean crustaceans, echinoderms, bivalves, and larger fauna are replaced or outlasted by small opportunistic polychaetes (Harper and others 1981; Gaston 1985; Rabalais and others 2002; Montagna and Ritter 2006). It is predicted that there may be limited mixing between the pit and the water column above it. This may cause stratification within the excavation pit. Water column stratification is commonly correlated with hypoxia (Ritter and Montagna 1999; Rabalais and others 2002; Applebaum and others 2005). Low dissolved oxygen levels have been documented in excavation pits in a sand mining study in estuaries (Johnston 1981).

The third potential physical change that may impact macrobenthic communities is a change in sediment grain size distribution. A low-flow zone can occur within a dredge pit, which promotes deposition of fine-grained sediment (Johnston 1981). Correlations between sediment grain size and benthic organisms are strong and well documented (Young and Rhoads 1971; Rhoads 1974; Mannino and Montagna 1997; Palmer 2006). The in-filling of a dredge excavation pit with finer sediments than the original sediment size was documented in offshore South Carolina (Jutte and others 2002). The deposition of fine-grained sediments is not certain however. Shelf sediments in various locations up to 60 m deep in the northern Gulf of Mexico are frequently reworked due to storms and river discharge (Kennicutt and others 1995).

Approximately 2 million cubic meters (2.5 million cubic yards) were excavated from offshore of the westernmost coastal segment of Louisiana, between Calcasieu and Sabine Passes. The purpose of this excavation was to provide sandy substrate for local beach nourishment at Holly Beach, Louisiana. Louisiana's westernmost coastal segment has been subject to beach erosion since the late 19th century because of decreased supply of sediment to the beaches (Campbell and others 2005; Penland and others 2005). This reduction in sediment supply is partially the fault of decreased sediment loading of rivers due to channel and flow alterations and partially because of restrictions in long-shore sediment transport as a result of the construction of 3-km long jetties at Calcasieu Pass and offshore breakwaters at Holly Beach (Campbell and others 2005; Penland and others 2005). The purpose of the current study is to investigate the impact created by the dredge excavation pit on macrobenthic communities. There are two hypotheses in this study. The first hypothesis (H_1) is that the sediment and water column will be different in the pit compared to the surrounding area. The second hypothesis (H_2) is that the different physical environment in the pit compared to the surrounding area will result in significant differences in benthic macrofaunal communities.

Methods

Study Design

This study is located in and around a dredge excavation pit located 7 km (4 mi) south of Holly Beach, Louisiana, and 28 km (17 mi) east of the Texas-Louisiana border (Fig. 1). The original pre-dredging depth was 8 m. The pit was excavated in April, 2003. A total of eight stations were sampled between June 10 and 11, 2006, 3 years after excavation (Fig. 1). Two sampling stations were located within the pit (stations 1 and 2), two were 20 m from the pit edge (stations 4 and 5), one was 100 m away from the pit edge (station 6), one was 200 m from the pit edge (station 3), and two were at least 1 km from the edge of the pit (stations 7 and 8). Macrobenthic samples were taken at each station, along with hydrographic measurements in the water column and sediment samples.

Hydrographic Measurements

Vertical hydrographic profiles of the water column were taken at each station. Measurements were taken at six evenly spaced depth intervals (bottom, surface, and 20, 40, 60, 80% of the total depth) in each profile. A multiparameter YSI 600XLM datasonde was used to measure temperature (°C), salinity (psu), dissolved oxygen (mg l^{-1}), and pH at each station.

Macrofauna

Macrofauna samples were collected using SCUBA. Macrofauna were sampled with 6.7-cm diameter core tubes and sectioned at depth intervals of 0–3 cm and 3–10 cm. Five

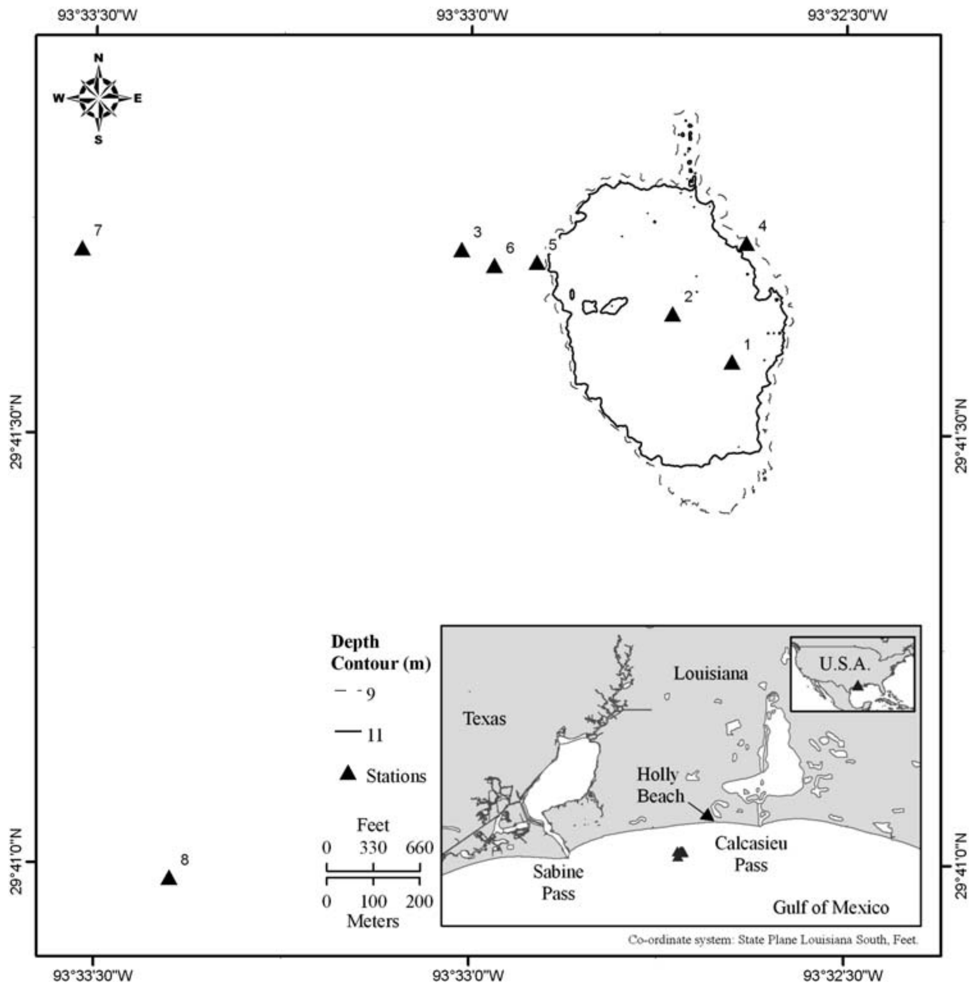

Fig. 1 Locations of sampling stations. Bathymetry is derived from a June 2006 survey

samples were taken at each station and immediately preserved with 5% buffered formalin. In the laboratory, macrofauna were sorted on 0.5-mm sieves and identified to the lowest taxonomic level possible, usually the species level. Organisms from each sample were pooled into higher taxonomical categories (Crustacea, Mollusca, Polychaeta, and Others) and dried for 24 h at 55°C to determine dry weight biomass. The dried categories were then weighed to the nearest 0.01 mg. Molluscs were placed in 1 N HCl from a few minutes to an hour until carbonate shells were dissolved and washed before drying.

Sediment Size Analysis

Sediment samples were collected with 6.7-cm diameter core tubes and sectioned at depth intervals of 0–3 cm and 3–10 cm. Percent contribution by weight was measured for four size classes: rubble, sand, silt, and clay. To determine grain size, a 20-cm^3 sediment sample was mixed with 50 ml of hydrogen peroxide and 75 ml of deionized water to digest organic material in the sample. The sample was wet sieved through a 62-μm mesh stainless steel screen using a vacuum pump and a Millipore Hydrosol SST filter holder to separate rubble and sand from silt and clay. After drying, the rubble and sand were separated on a 125-μm screen. In this study rubble is defined as sediment over 125 μm in diameter and is usually composed of shells, gravel, debris, and very coarse sand. The silt and clay fractions were measured using pipette analysis. The sediment size analysis follows the methods in Folk (1964).

Statistical Analysis

Species diversity was calculated using Hill's number one (N1) diversity index, which is the exponential form of the Shannon H' diversity index (Hill 1973). Hill's N1 was used because it has units of numbers of species, and is more interpretable than most other diversity indices (Ludwig and Reynolds 1988).

A one-way analysis of variance (ANOVA) was used to test for differences in macrofauna abundance, biomass, and Hill's N1 diversity between stations. Abundance and biomass were log transformed (log(x+1)) prior to analysis. Where significant differences were detected, Tukey multiple comparison tests were used to aid the explanation of the significant differences. All univariate analyses were performed using SAS software (SAS Institute Inc. 1999).

Community structure and biomass of infaunal species was analyzed by nonmetric multi-dimensional scaling (MDS). Differences and similarities among communities were highlighted using cluster analysis. Species abundance data was log transformed prior to analysis and used a Bray-Curtis similarity matrix to create the MDS plot. MDS was performed using Primer software (Clarke and Gorley 2006).

Principal Component Analysis (PCA), a parametric multivariate method, was used to assess relationships between physical variables (sediment grain size, bottom depth, and hydrographic measurements) characteristic of stations. Water quality variables were log-transformed prior to analysis. Sediment sizes were arcsine root transformed because they were in percentage form. Results are presented in bivariate plots as station scores and as variable loads. PCA analyses were performed using SAS software (SAS Institute Inc. 1999).

Relationships between macrofauna communities and environmental factors were investigated using the Biota-Environment (BIO-ENV) procedure. The BIO-ENV procedure is a multivariate method that matches biotic (i.e., macrofauna community structure) with environmental variables (Clarke and Ainsworth 1993; Clarke and Warwick 2001). For this study, the macrofauna species abundance MDS ordination was compared with sediment size and water quality variables measured at the bottom of the water column. The significance of relationships were tested using RELATE, a nonparametric form of the mantel test. The BIO-ENV and RELATE procedures were calculated with Primer software (Clarke and Gorley 2006).

Results

Macrofauna

There were a total of 50 species found in this study (Table 1). The most abundant species overall were *Mediomastus ambiseta* (3700 m^{-2}, 55%) followed by *Paraprionospio pinnata* (1200 m^{-2}, 18%) and *Magelona phyllisae* (300 m^{-2}, 5%). These three most abundant species were all polychaetes. The overall most abundant species, *M. ambiseta*, was not present in stations 1 and 3, and had an abundance of only 57 organisms m^{-2} at station 2. *P. pinnata* occurred at densities greater than 600 m^{-2} at all stations except station 3 where the density was less than 200 m^{-2}. The polychaete *Spiophanes bombyx* was the most abundant species (1100 m^{-2}) at station 3 and was not found at any other stations. The total abundance was comprised of 97–100% polychaetes inside the pit as opposed to 72–98% outside the pit (Table 2). Only three species were found at each of station 1 and 2, combining to make a total of four different species. Three out of the four species found at stations 1 and 2 were polychaetes, the most abundant being *P. pinnata* with an abundance of 1400–1600 n m^{-2}, out of a total of abundance of 1500–1700 n m^{-2} (Table 1).

Macrofauna communities were divided into three distinct groups based on 40% similarity among species abundances at each station (Fig. 2). The first group contained only station 3 and was only 22% similar to the other stations. The second group contained stations 1 and 2, the stations located in the dredge excavation pit. Stations 1 and 2 were 73% similar to each other and 32% similar to stations 4–8. The third group contained stations 4 through 8. Stations 5 and 6 were 54% similar to each other and 44% similar to stations 4, 7, and 8. There was 61% similarity between stations 7 and 8.

Stations were grouped into three different groups based on biomass for each taxa at each station (Fig. 3). Stations 1 and 2 made up one group and were 32% different than all of the other stations. The other stations were separated into two groups with 50% similarity between the two. One group contained stations 5 and 6, while the other contained stations 3, 4, 7, and 8. All stations contained 87.1–100.0% polychaetes by weight; however, the highest proportion of polychaetes were found at stations 1 and 2, inside the pit (Table 2).

There were significant differences in macrofaunal abundance, biomass, and N1 diversity between stations (Table 3). Station 1 had significantly lower abundance than the three closest stations to the pit (stations 4, 5, and 6) and station 7. The stations inside the pit had significantly lower total biomass than stations 5 and 6, the two closest stations to the west side of the pit. N1 diversity at both stations 1 and 2 was significantly lower than at 3, 4, and 5. Stations 1 and 2, inside the pit, had the lowest total abundance (<1700 n m^{-2}), biomass (g m^{-2}), and N1 diversity out of all of the stations (Table 3). Stations 5 and 6 had the highest abundance (>16,000 n m^{-2}) and biomass (>5 g m^{-2}), but had relatively moderate numbers of dominant species (N1 diversity values; 3.5–3.6).

Physical Variables

All water quality and sediment variables for all stations were merged for Principal Component Analysis (PCA; Fig. 4). The first and second principal components (PC1 and PC2) explained 54% and 28% of the variation within

Table 1 Species abundance for each station and as an overall mean

Species name	Taxa Group	Station								Mean	Mean as	Cumulative
		1	2	3	4	5	6	7	8		%	%
Mediomastus ambiseta	P	0	57	0	2950	10,835	11,459	2212	1985	3687	55.4	55.4
Paraprionospio pinnata	P	1588	1418	170	1418	624	794	2212	1191	1177	17.7	73.0
Magelona phyllisae	P	0	0	0	0	2042	454	57	57	326	4.9	77.9
Nemertinea (unidentified)	N	0	0	340	113	908	794	57	170	298	4.5	82.4
Cossura delta	P	0	0	57	340	511	340	57	113	177	2.7	85.1
Sigambra tentaculata	P	57	57	0	340	284	227	113	170	156	2.3	87.4
Spiophanes bombyx	P	0	0	1,135	0	0	0	0	0	142	2.1	89.5
Tellina sp.	M	57	0	0	0	284	227	0	0	71	1.1	90.6
Glycinde solitaria	P	0	0	0	57	284	170	57	0	71	1.1	91.7
Diopatra cuprea	P	0	0	0	0	113	340	0	0	57	0.9	92.5
Phoronis architecta	O	0	0	57	0	57	227	0	0	43	0.6	93.1
Oligochaetes (unidentified)	P	0	0	0	57	0	57	0	227	43	0.6	93.8
Apoprionospio pygmaea	P	0	0	284	0	0	0	0	0	35	0.5	94.3
Anaitides longipes	P	0	0	57	0	0	170	0	0	28	0.4	94.7
Bivalvia (unidentified)	M	0	0	57	0	0	113	0	0	21	0.3	95.1
Sthenelais sp.	P	0	0	113	0	0	0	0	57	21	0.3	95.4
Ampelisca abdita	C	0	0	0	0	57	113	0	0	21	0.3	95.7
Ophiuroidea (unidentified)	OP	0	0	0	57	0	113	0	0	21	0.3	96.0
Turbellaria (unidentified)	O	0	0	0	57	57	0	0	0	14	0.2	96.2
Mulinia lateralis	M	0	0	57	0	0	57	0	0	14	0.2	96.4
Syllis sp.	P	0	0	0	0	57	0	0	57	14	0.2	96.7
Trachypenaeus constrictus	C	0	0	0	0	0	113	0	0	14	0.2	96.9
Calappidae (unidentified)	C	0	0	57	0	0	57	0	0	14	0.2	97.1
Anthozoa (unidentified)	O	0	0	0	0	57	0	0	0	7	0.1	97.2
Gastropoda (unidentified)	M	0	0	0	0	0	0	57	0	7	0.1	97.3
Nassarius sp.	M	0	0	0	0	0	0	0	57	7	0.1	97.4
Nuculana sp.	M	0	0	0	0	0	0	0	57	7	0.1	97.5
Malmgreniella sp.	P	0	0	0	0	0	57	0	0	7	0.1	97.6
Paleanotus chrysolepis	P	0	0	0	0	0	57	0	0	7	0.1	97.7
Paleanotus sp.	P	0	0	0	0	57	0	0	0	7	0.1	97.8
Eurythoe sp.	P	0	0	0	57	0	0	0	0	7	0.1	97.9
Ancistrosyllis papillosa	P	0	0	0	0	57	0	0	0	7	0.1	98.0
Ancistrosyllis sp.	P	0	0	0	0	0	57	0	0	7	0.1	98.1
Pilargiidae (unidentified)	P	0	0	0	0	0	0	57	0	7	0.1	98.3
Podarke obscura	P	0	0	57	0	0	0	0	0	7	0.1	98.4
Websterinereis tridentata	P	0	0	0	0	0	57	0	0	7	0.1	98.5
Laeonereis culveri	P	0	0	0	0	0	57	0	0	7	0.1	98.6
Nereidae (unidentified)	P	0	0	0	0	0	57	0	0	7	0.1	98.7
Lumbrineridae (unidentified)	P	0	0	0	0	0	57	0	0	7	0.1	98.8
Dorvillea sp.	P	0	0	0	57	0	0	0	0	7	0.1	98.9
Maldanidae (unidentified)	P	0	0	0	0	0	57	0	0	7	0.1	99.0
Ampharete parvidentata	P	0	0	0	0	57	0	0	0	7	0.1	99.1
Sabellidae (unidentified)	P	0	0	0	0	0	0	0	57	7	0.1	99.2
Callianassa biformis	C	0	0	0	0	57	0	0	0	7	0.1	99.3
Paguridae juv.	C	0	0	57	0	0	0	0	0	7	0.1	99.4
Pinnixa sp.	C	0	0	57	0	0	0	0	0	7	0.1	99.5
Oxyurostylis sp.	C	0	0	0	57	0	0	0	0	7	0.1	99.6

Table 1 continued

Species name	Taxa Group	Station								Mean	Mean as	Cumulative
		1	2	3	4	5	6	7	8		%	%
Oxyurostylis smithi	C	0	0	0	0	57	0	0	0	7	0.1	99.7
Corophium sp.	C	0	0	0	0	0	57	0	0	7	0.1	99.9
Listriella sp.	C	0	0	57	0	0	0	0	0	7	0.1	100.0
Total		1702	1532	2609	5559	16,451	16,338	4879	4198	6658	100	
Total number of species		3	3	15	12	19	27	9	12	12.5		

Abundances are in n m $^{-2}$. Taxa groups: P = polychaete, N = nemertean, M = mollusc, C = crustacean, OP = ophiuroid, O = other

Table 2 Abundance and biomass of each major taxa group

Taxa Group	Station								Mean	Mean
	1	2	3	4	5	6	7	8		as %
Abundance (n m^{-2})										
Polychaete	1645	1532	1872	5219	14,919	14,295	4765	3801	6006	90.7
Nemertean	0	0	340	113	908	851	57	170	305	4.6
Mollusc	57	0	113	0	284	397	57	113	128	1.9
Crustacean	0	0	227	57	170	340	0	0	99	1.5
Other	0	0	57	57	170	227	0	0	64	1.0
Ophiuroid	0	0	0	57	0	113	0	0	21	0.3
Total	1702	1532	2609	5503	16,451	16,224	4879	4084	6623	100.0
% Polychaetes	96.7	100.0	71.7	94.8	90.7	88.1	97.7	93.1		
Biomass (g m^{-2})										
Polychaete	0.1	0.3	1.0	1.1	5.4	7.3	1.6	0.7	2.2	91.9
Mollusc	0.0	0	0.0	0	0.0	0.8	0.0	0.0	0.1	4.6
Nemertean	0	0	0.1	0.0	0.2	0.1	0.0	0.0	0.1	2.1
Crustacean	0	0	0.0	0.0	0.1	0.1	0	0	0.0	1.0
Other	0	0	0.0	0.0	0.0	0.0	0	0	0.0	0.2
Ophiuroid	0	0	0	0.0	0.0	0.0	0	0	0.0	0.1
Total	0.1	0.3	1.1	1.1	5.7	8.4	1.6	0.7	2.4	100.0
% Polychaetes	99.6	100.0	87.1	99.3	95.2	87.6	98.6	93.3		

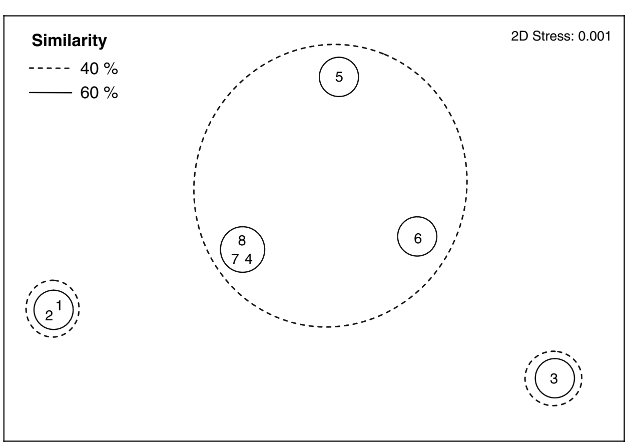

Fig. 2 Nonmetric Multi-Dimensional Scaling analysis of species abundances at each station

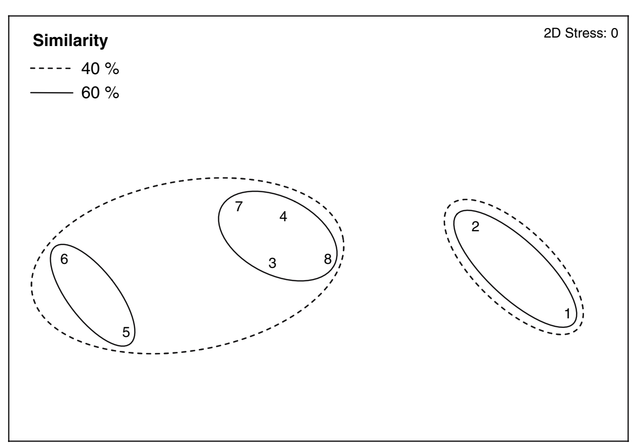

Fig. 3 Nonmetric Multi-Dimensional Scaling analysis of biomass of each taxa at each station

the data set respectively (total 82%). Along PC1, depth and fine particles (clay and silt) are inversely related to temperature and coarse sediment particles (sand and rubble). Along PC2 salinity is inversely related to dissolved oxygen and pH (Fig. 4a). PC1 is approximated by sediment grain size parameters, water temperature, and depth. PC2 is approximated by pH, dissolved oxygen and salinity. Along PC1, the stations are divided into three groups: stations 1 and 2 (inside the pit); stations 4, 7, and 8; and stations 3, 5, and 6 (Fig. 4b). Stations 1 and 2 were the deepest stations (both 11.1 m) and had the highest proportion of clay in their sediments (>80%; Table 4). All other stations were between 7.9 and 8.3 meters deep. Stations 3, 5, and 6 had the highest proportion of sand (42–93%) and rubble (5–15%) out of all of the stations. The sediment at station 3 was very different from the other stations in that it contained 93% sand and less than 1% clay and silt combined. The sediment at stations 4, 7, and 8 contained 55–69% clay, 5–27% sand, and less than 1% rubble.

The water quality at the bottom depths of each station were fairly constant among stations with regards to salinity (32.12–32.23 psu), temperature (27.73–27.93°C) and pH (7.84–7.89; Table 4). Bottom dissolved oxygen values varied a small amount between stations (3.0–3.5 mg l^{-1}). Mean dissolved oxygen values for the entire water column at the stations (1 and 2) located inside the pit were 4.9–5.0 mg l^{-1} as opposed to 5.7–6.0 mg l^{-1} at the rest of the stations. The mean values for temperature, salinity, and pH for stations inside the pit were within the range of means calculated for the other stations outside the pit.

Linking Macrofauna with Physical Variables

As determined by the BIO-ENV procedure, macrofauna communities were more highly correlated with sediment, depth, and bottom temperature than any other physical variable (Table 5). The highest correlation with the macrofauna communities was with the combination of silt, clay, and depth ($\rho = 0.854$). The relationship between macrofauna communities and the silt, clay, depth combination had a significance level of 0.5%.

Discussion

The first hypothesis (H_1) is that the sediment and water column will be different in the pit compared to the

Table 3 Analysis of variance and Tukey grouping for N1 diversity, biomass, and abundance at each station

Source	Degrees of freedom	Type III sum of squares	Mean square	F value	Pr > F
Abundance (n m^{-2})					
Station	7	56.507	8.072	5.06	0.0006
MS(Error)	32	51.012	1.594		
Diversity (N1)					
Station	7	49.201	7.029	5.4	0.0004
MS(Error)	32	41.689	1.303		
Biomass (g m^{-2})					
Station	7	13.008	1.858	6.42	<.0001
MS(Error)	32	9.263	0.289		

Abundance								
Mean (n m^{-2})	16,451	16,224	5503	4879	4084	2609	1532	1702
Station	5	6	4	7	8	3	2	1
Tukey groupings								
Biomass								
Mean (g m^{-2})	8.38	5.72	1.60	1.10	1.07	0.71	0.26	0.13
Station	6	5	7	3	4	8	2	1
Tukey groupings								
N1 Diversity								
Mean	4.06	3.87	3.61	3.54	3.31	2.60	1.22	1.02
Station	3	4	5	6	8	7	2	1
Tukey groupings								

All analyses were carried out using log transformed data, MS = mean square

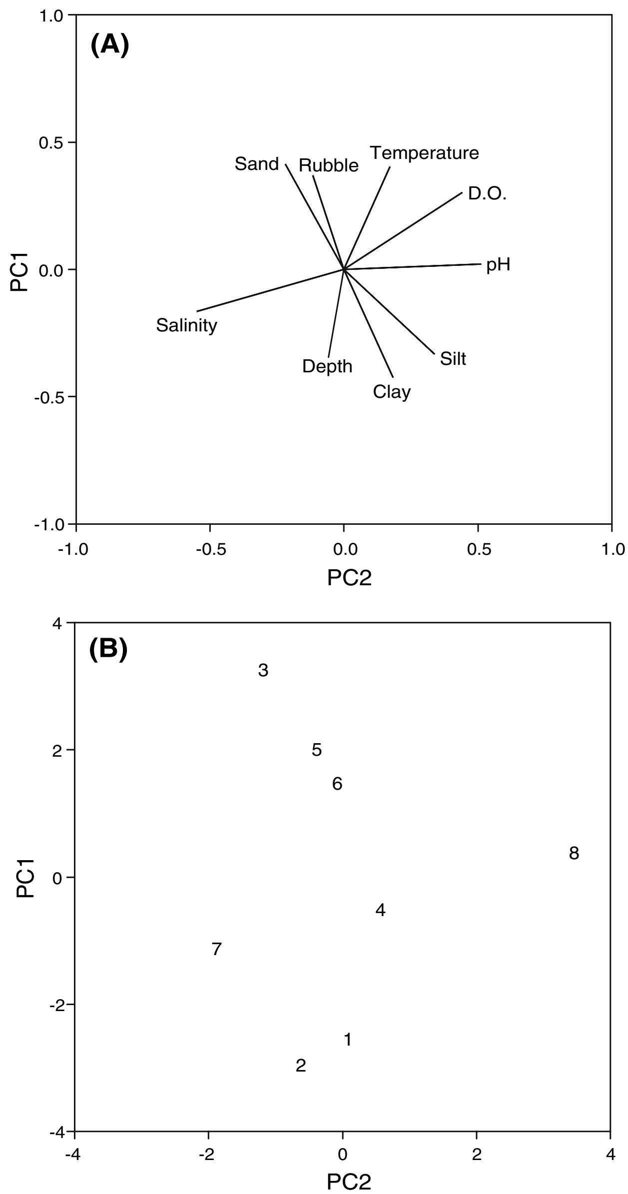

Fig. 4 Plots of the first two principal components (PC) resulting from analysis of sediment data. (**a**) PC variable loadings and (**b**) PC station scores. D.O. = Dissolved Oxygen. PC1 accounted for 53.5% of the total variation in the data set, while PC2 accounted for 28.1% (Total 81.5%)

surrounding area. The two stations (1 and 2) inside the pit were approximately 3 m deeper than the surrounding stations (Table 4). The sediment grain size distribution could be divided into three distinct groups (Fig. 4, Table 4). The three stations (3, 5, and 6) within 200 m of the west side of the pit had coarser sediments than all other stations. These three stations had higher rubble and sand contents and lower silt and clay contents than all other stations. Stations 4, 7, and 8 had an intermediate grain size distribution, while the stations (1 and 2) within the pit had the finest sediment. The sediment grain size distributions at the excavated stations contained at least 80% clay and less than 1% sand. Sediment at all other stations contained 1% to 69% clay and 5% to 93% sand.

Accretion from 18.5 m to 11 m inside the pit was approximately 4 m (13 ft) between April, 2003 and December, 2004 (21 months) and approximately 3.5 m (11 ft) between December, 2004 and June, 2006 (17 months). This accretion decreased the pit depth from the original 18.5 m to 11 m between April, 2003 and June, 2006. Lower flow velocities inside the pit favor deposition of finer sediment, which is the dominant reason why sediment inside the pit is finer than outside it. It is possible that the in-filling of the excavation pit may be related to the two major hurricanes that hit the dredge pit within nine months prior to June, 2006 sampling. Hurricanes Katrina and Rita were both category 5 strength on the Saffir-Simpson scale, although they both weakened as they approached the study site. While the eye of Hurricane Katrina passed within 400 km east of the study area as a Category 4 hurricane in August, 2005, Hurricane Rita passed directly over the study area as a Category 3 hurricane in September, 2005. During Hurricane Rita, Holly Beach was exposed to a 5–6 m (16–20 ft) storm surge and consequently suffered beach erosion and severe building destruction (Turner and others 2006; USGS 2005). However, in a study using a two-dimensional vertical (2DV) simulation model by Nairn and others (2006, 2007), it was noted that predicted pit in-filling, calculated without the consideration of extreme events such as hurricanes, matched actual in-filling measurements well. This study by Nairn and others (2006, 2007) implies that the effects of the hurricanes on the pit were minor.

Mean water column and bottom temperature, salinity, and pH were similar at all stations (Table 4). Mean vertical profile dissolved oxygen concentrations were 0.7–1.1 mg l^{-1} lower at stations inside the pit than the rest of the stations; however, bottom dissolved oxygen values inside the pit were within the range of bottom dissolved oxygen values of the undisturbed stations. Bottom dissolved oxygen concentrations both in and out of the dredge pit were between 3.0 and 3.5 mg l^{-1}. There were no anoxic or hypoxic conditions observed as predicted might occur by Baird and Associates (2005). Hypoxia episodically occurs between May and September in the northern Gulf of Mexico with peak occurrences between mid-July and mid-August (Harper and others 1981; Gaston 1985; Rabalais and others 2002). It is estimated that bottom water hypoxia occurred approximately 25% of the time in mid-summer weeks between 1985 and 2001 in the same area as this current study (Rabalais and others 2002). While hypoxia was not observed in this study, it is improbable that hypoxia does not occur in the study area. There is a high probability that a single bottom sample on a single day would not detect hypoxia in the study area. The single

Table 4 Summary of physical parameters measured at each station

Station	Mean rubble (%)	Mean sand (%)	Mean silt (%)	Mean clay (%)	Mean temp (°C)	Mean salinity (psu)	Mean D.O. (mg l^{-1})	Mean pH	Bottom temp (°C)	Bottom salinity (psu)	Bottom D.O. (mg l^{-1})	Bottom pH	Total depth (ft)	Total depth (m)
1	0.0	0.9	19.0	80.1	28.33	31.74	4.92	7.99	27.79	32.22	3.12	7.88	36.4	11.1
2	0.0	0.3	17.3	82.4	28.36	31.74	4.99	7.99	27.73	32.23	3.11	7.87	36.3	11.1
3	5.7	93.1	0.2	1.0	28.86	31.59	5.85	8.04	27.92	32.20	3.32	7.87	26.3	8.0
4	0.2	26.5	18.2	55.2	27.55	34.44	5.95	7.32	27.80	32.20	3.27	7.88	26.8	8.2
5	15.8	54.5	8.7	21.0	28.71	31.57	5.81	8.04	27.91	32.20	3.30	7.87	27.1	8.3
6	10.0	42.1	10.5	37.3	28.81	31.71	5.98	8.04	27.91	32.20	3.30	7.87	26.2	8.0
7	0.3	18.0	16.8	64.9	28.76	31.60	5.71	8.03	27.84	32.22	2.98	7.84	26.0	7.9
8	0.5	5.3	25.7	68.5	28.62	31.48	5.88	8.05	27.93	32.12	3.45	7.89	26.3	8.0

Temp = temperature, D.O. = dissolved oxygen

measurement also says nothing about the extent, intensity, duration, and frequency of any potential hypoxic events. Overall, water quality is the same inside and outside the pit.

The second hypothesis (H_2) is that the different physical environment in the pit compared to the surrounding area will result in significant differences in benthic macrofaunal communities. Based on species abundances, macrofauna communities in the pit were 32% similar to the other stations outside the pit, except for station 3, which had only 22% similarity with any other station (Fig. 2). Only four macrofauna species were found inside the pit. The polychaete *Paraprionospio pinnata* made up over 90% of all organisms found in the pit (Table 1). The density of *P. pinnata* inside the pit (1400–1600 n m^{-2}) was similar to stations 4, 7, and 8 (1200–2200 n m^{-2}) outside the pit. *Tellina* sp. was the only mollusk found within the pit and was only found in one sample. The polychaete *Mediomastus ambiseta* occurred in high densities (2000–11,000 n m^{-2}) in all stations outside the pit except for station 3 where none of the species were found. *M. ambiseta* was found in very low densities (0–57 n m^{-2}) inside the pit. In a previous study located within 5–10 km of the current study, *M. californiensis* (probably misidentified *M. ambiseta* specimens) was found to be sensitive to hypoxia (Gaston 1985). This would support the prediction that the pit experienced more hypoxia or anoxia than the surrounding unexcavated area. However, Mannino and Montagna (1997) found that *M. ambiseta* was more abundant in sandier sediments than other sediment sizes, so the absence of *M. ambiseta* in the pit could be a result of a different sediment size distribution. The macrofaunal community in this current study relates highest with the combination of silt and clay concentrations in the sediment and station depth (Table 5). Overall, macrofauna communities are different inside the pit, correlating with the change in sediment size rather than from hypoxia or any other water column variable.

Based on macrofaunal biomass of each taxa, there was at least 68% difference ($\leq$ 32% similar) between communities inside and outside of the pit (Fig. 3). The stations in the pit contained organisms from only 1 or 2 taxa groups compared to 3–6 taxa groups at all other stations (Table 2). Polychaetes were still the most dominant taxa by weight at all stations (87.1–100%) but had the greatest dominance by weight at Stations 1 and 2, inside the pit (99.6–100%).

The two stations inside the pit had lower total abundance, biomass, and N1 diversity than any other station outside the pit, although this relationship was only significant with some of the stations outside of the pit (Table 3). The comparatively low abundance, biomass, and diversity is typical of a disturbed area (Pearson and Rosenberg 1978; Gaston 1985; Montagna and others 2002; Palmer and others 2002; Balthis 2006). The constant accretion of sediment of approximately 2.4 m yr^{-1} (8 ft yr^{-1}) inside the dredge pit since excavation in April 2003, in addition to any possible hypoxic events that may occur, will hinder the succession of the macrofaunal community (Rhoads and

Table 5 Environmental variables that correlated highest with macrofaunal communities as determined by the BIO-ENV procedure

No. of variables	Pearson correlation (ρ_w)	Variables selected
3	0.854	Silt, Clay, Depth
2	0.829	Silt, Depth
4	0.828	Sand, Silt, Clay, Depth
3	0.823	Sand, Silt, Depth
3	0.817	Sand, Clay, Depth
5	0.806	Sand, Silt, Clay, Temperature, Depth
4	0.799	Sand, Silt, Temperature, Depth
1	0.797	Sand
2	0.796	Clay, Depth
4	0.794	Silt, Clay, Temperature, Depth

The highest correlation had a significant level of 0.5%

others 1978; Peterson 1985). Macrofaunal communities recovered within 30 months of dredging in a series of meter-deep South Carolina dredge pits (Jutte and others 2002). The original pit excavation depth in the present study was 10 times deeper than the depth in Jutte and others (2002); therefore it is understandable that the recovery was not as rapid. This greater depth will require a longer stabilization and physical recovery time. At the current rate of sedimentation, the pit should be filled up within 1.3 years; however, the accretion rate is predicted to slow so that the dredge pit will not be totally full until 2010 or 2011 (Nairn and others 2006, 2007).

Thirty-eight months after excavation (April 2003–June 2006), the excavation pit is still physically and biologically different from the surrounding area. Although water quality appeared to be very similar inside and outside the pit at the time of sampling, the water column is temporally dynamic, and a survey over time would be required to prove that water quality played no vital role in the differences in macrofaunal communities. The sediment inside the pit is smaller in size than outside the pit. The difference in sediment size between inside and outside of the pit correlated strongly with macrofaunal community differences in the study area. The high accretion rates occurring in the pit are deleterious to many organisms. Predicted reduced accretion rates should allow larger numbers of more diverse organisms to settle and survive in the pit. The macrofaunal community inside the pit is not likely to recover until the sediment inside the pit is similar to that occurring outside the pit and any accretion is more stable.

Acknowledgments The authors would like to thank Phil Hanley, Chris Fuller, Lilo Burda, and Anne Williams for sample collection; Larry Hyde and Rick Kalke for providing sampling equipment and assistance in macrofauna identification; April Gossmann for carrying out sediment analysis; and Carrol Simanek for data management. This project was funded via a subcontract to the University of Texas Marine Science Institute (# 10964) under contract number 1435-01-05-RP−39150 between the Minerals Management Service (MMS) and Baird and Associates.

References

Applebaum S, Montagna PA, Ritter C (2005) Status and trends of dissolved oxygen in Corpus Christi Bay, Texas, U.S.A. Environmental Monitoring and Assessment 107:297–311

Baird and Associates Ltd (2005) Examination of the Physical and Biological Implications of Using Buried Channel Deposits and Other non Topographic Offshore Features as Beach Nourishment Material, Volume 1 - Technical Proposal. Minerals Management Service

Balthis WL, Hyland JL, Bearden DW (2006) Ecosystem responses to extreme natural events: Impacts of three sequential hurricanes in Fall 1999 on sediment quality and condition of benthic fauna in the Neuse River Estuary, North Carolina. Environmental Monitoring and Assessment 119:367–389

Byrnes MR, Hammer RM, Thibaut TD, Snyder DB (2004) Physical and biological effects of sand mining offshore Alabama,U.S.A. Journal of Coastal Research 20(1):6–24

Campbell T, Benedet L, Finkl CW (2005) Regional strategies for coastal restoration along the Louisiana Chenier Plain. Journal of Coastal Research 44:268–283

Clarke KR, Ainsworth M (1993) A method of linking multivariate community structure to environmental variables. Marine Ecology Progress Series 92:205–219

Clarke, KR, Gorley RN (2006) PRIMER v6: User Manual / Tutorial. PRIMER-E: Plymouth, United Kingdom

Clarke, KR, Warwick RM (2001) Change in Marine Communities: An Approach to Statistical Analysis and Interpretation. 2nd Ed. PRIMER-E: Plymouth, United Kingdom

Finkl CW, Khalil SM (2005) Offshore Exploration for Sand Sources: General Guidelines and Procedural Strategies along Deltaic Coasts. Journal of Coastal Research 44:203–233

Folk RL (1964) Petrology of Sedimentary Rocks. The University of Texas, Austin. Texas

Gaston GR (1985) Effects of hypoxia on macrobenthos of the Inner Shelf of Cameron, Louisiana. Estuarine Coastal Shelf Science 20:603–613

Grassle JF, Grassle JP (1974) Opportunistic life histories and genetic systems in marine benthic polychaetes. Journal of Marine Research 32(2):253–284

Harper DE, McKinney LD, Salzer RR, Case RJ (1981) The occurrence of hypoxic bottom water off the Upper Texas Coast and its effects on the benthic biota. Contributions of Marine Science 24:53–79

Hill MO (1973) Diversity and evenness: a unifying notation and its consequences. Ecology 54:427–432

Hilton MJ (1994) Applying the principle of sustainability to coastal sand mining: The case of Pakiri-Mangawhai Beach, New Zealand. Environmental Management 18(6):815–829

Johnston SA Jr (1981) Estuarine dredge and fill activities: A review of impacts. Environmental Management 5(5):427–440

Jutte PC, Van Dolah RF, Gayes PT (2002) Recovery of Benthic Communities Following Offshore Dredging, Myrtle Beach, South Carolina. Shore & Beach 70(3):25–30

Kennicutt MC II, Schroeder WW, Brooks JM (1995) Temporal and spatial variations in sediment characteristics on the Mississippi-Alabama continental shelf. Continental Shelf Research 15(1): 1–18

Lu L, Wu RSS (2000) An experimental study on recolonization and succession of marine macrobenthos in defaunated sediment. Marine Biology 136(2):291–302

Ludwig JA, Reynolds JF (1988) Statistical Ecology: a Primer on Methods and Computing. John Wiley and Sons, New York, p. 368

Mannino A, Montagna PA (1997) Small-scale spatial variation of macrobenthic community structure. Estuaries 20(1):159–173

Montagna PA, Kalke RD (1992) The effect of freshwater inflow on meiofaunal and macrofaunal populations in the Guadalupe and Nueces Estuaries, Texas. Estuaries 15(3):307–326

Montagna PA, Kalke RD, Ritter C (2002) Effect of restored freshwater inflow on macrofauna and meiofauna in upper Rincon Bayou, Texas, USA. Estuaries 25(6B):1436–1447

Montagna PA, Ritter C (2006) Direct and indirect effects of hypoxia on benthos in Corpus Christi Bay, Texas, U.S.A. Journal of Experimental Marine Biology and Ecology 330(1):119–131

Nairn R, Johnson JA, Hardin D, Michel J (2004) A biological and physical monitoring program to evaluate long-term impacts from sand dredging operations in the United States outer continental shelf. Journal of Coastal Research 20(1):126–137

Nairn, RB, Lu Q, Drucker BS (2006) Evolution of dredged pits offshore Louisiana and buffers around seabed infrastructure.

Proceedings of the 30th International Conference on Coastal Engineering 3578–3590

Nairn, RB, Lu Q, Langendyk SK, Montagna PA, Powers SP (2007) Examination of the Physical and Biological Implications of Using Buried Channel Deposits and other Non-Topographic Offshore Features as Beach Nourishment Material. U.S. Dept. of the Interior, Minerals Management Service. OCS Study MMS 2007–048

Palmer TA, Montagna PA, Kalke RD (2002) Downstream effects of restored freshwater inflow to Rincon Bayou, Nueces Delta, Texas, USA. Estuaries 25(6B):1448–1456

Palmer TA (2006) Initial Effects of Opening Packery Channel on Estuarine Macrofauna in Corpus Christi Bay, Texas. Masters Thesis. University of Texas at Austin

Pearson TH, Rosenberg R (1978) Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Oceanography and Marine Biology. An Annual Review 16: 229–311

Penland S, Connor PF Jr, Beall A, Fearnley S, Williams SJ (2005) Changes in Louisiana's Shoreline: 1855–2002. Journal of Coastal Research 44:7–39

Peterson CH (1985) Patterns of lagoonal bivalve mortality after heavy sedimentation and their paleoecological significance. Paleobiology 11(2):139–153

Pokryfki L, Randall RE (1987) Nearshore hypoxia in the bottom water of the northwestern Gulf of Mexico from 1981 to 1984. Marine Environmental Research 22(1):75–90

Rabalais NN, Turner RE, Wiseman WJ (2002)Gulf of Mexico hypoxia, A.K.A. "The dead zone" Annual Review of Ecology and Systematics 33:235–263

Renaud M (1986) Hypoxia in Louisiana coastal waters during 1983: implications for fisheries. Fishery Bulletin 84:19–26

Rhoads DC (1974) Organism-Sediment Relations on the Muddy Sea Floor. Oceanography and Marine Biology. An Annual Review 12:263–300

Rhoads DC, McCall PL, Yingst JY (1978) Disturbance and production on the estuarine seafloor. American Scientist 66(5):577–586

Ritter C, Montagna PA (1999) Seasonal hypoxia and models of benthic response in a Texas bay. Estuaries 22(1):7–20

Ritter C, Montagna PA, Applebaum S (2005) Short-term succession dynamics of macrobenthos in a salinity-stressed estuary. Journal of Experimental Marine Biology and Ecology 323(1):57–69

SAS Institute Inc (1999) SAS/STAT User's Guide: Version 8. SAS Institute Inc, Cary, North Carolina. p. 3809

Thistle D (1981) Natural physical disturbances and communities of marine soft bottoms. Marine Ecology Progress Series 6(2): 223–228

Turner RE, Baustian JJ, Swenson EM, Spicer JS (2006) Wetland sedimentation from Hurricanes Katrina and Rita. Science 314(5798):449–452

USGS (United States Geological Survey) (2005) http://www.coastal.er.usgs.gov/hurricanes/rita/index.html Accessed February 2007

Work PA, Fehrenbacher F, Voulgaris G (2004) Nearshore impacts of dredging for beach nourishment. Journal of Waterway Port Coastal and Ocean Engineering 130(6):303–311

Young DK, Rhoads DC (1971) Animal-sediment relations in Cape Cod Bay, Massachusetts. I. A transect study. Marine Biology 11(3):242–254